Preliminary results of optical downlink between QUBE satellite to the upgraded Optical Ground Station Oberpfaffenhofen - experiments towards quantum key distribution

Johannes Prell
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
johannes.prell@dlr.de

Shrestha Amita
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
amita.shrestha@dlr.de

Benjamin Rödiger
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
benjamin.roediger@dlr.de

René Rüddenklau
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
rene.rueddenklau@dlr.de

Alexandru Duliu
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
Alexandru-Octavian.Duliu@dlr.de

Anne-Laure Cheffot
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
anne-laure.cheffot@dlr.de

Jonas Rittershofer
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
jonas.rittershofer@dlr.de

Lisa Bardou
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
lisa.bardou@dlr.de

Christian Fuchs
Institute of Communications and Navigation, German Aerospace Center (DLR)
Oberpfaffenhofen, Germany
christian.fuchs@dlr.de

***Abstract*— Laser communication technology, especially QKD (Quantum Key Distribution), is coming more and more into practical operations. It is a maturing technology that enables the distribution of cryptographic key between two remote parties [1][3] for secure communication even in presence of quantum computers[3]. To demonstrate this technology DLR is part of the QUBE project to have a precursor mission for QKD from CubeSats in orbit as well as hosting and operating the ground-based counterpart the Optical Ground Station Oberpfaffenhofen (OGSOP).**

The OGS is equipped with an 80cm primary mirror, a Coudé path with optical bench, adaptive optics system, fiber coupling and a single photon detector. The ground station already performed successful downlinks from low Earth orbit (LEO) (Flying Laptop, CubeL and others) and geostationary platforms (Alphasat, Project BayernQSat), as well as aircrafts (Project QuNET) [4][11][13].

In the last year the ground station was upgraded from its basic configuration to adapt for multi-mission support and QKD experiments. Several features were integrated and upgraded at the telescope, in the Coudé path and on the optical bench. The focus of the upgrades was to connect the OGSOP (Optical Ground Station Oberpfaffenhofen) with the satellite QUBE. The target of compatibility could be achieved and improved from OGS side.

Knowledge from ground-to-ground-tests were considered to rebuild the receiving setups in an improved and more operational way. The QUBE satellite contains an optical terminal designed and developed by DLR to transmit two experimental quantum signals over the optical link. These sources were developed by the Ludwig-Maximilian University (LMU) of Munich and the Friedrich-Alexander University (FAU) in Erlangen.

On May the 2nd 2025 the OGSOP was able to catch the first light from QUBE and establish a link between both sides[2]. This started the optical communication commissioning phase of the satellite, including the classical communication terminal and the quantum light sources. This paper describes the entire setup, from satellite to ground detector, and presents the key achievements so far.

Keywords—Optical Ground Station Technology, Quantum Key Distribution, Laser Communication, CubeSats, New Space

I. Introduction

The German Aerospace Center (DLR) demonstrated the capabilities and advantages of free-space optical communication from small satellite platforms in the PIXL-1 mission, with the first OSIRIS4CubeSat payload in space [5][17]. As OSIRIS4CubeSat is a pure transmitter for classical optical communication, OSIRIS4QUBE marks the first evolution towards quantum key distribution (QKD).[5] The goal of the QUBE project is to transmit, in addition to the classical optical signal, experimental QKD signals from a 3U CubeSat to the Optical Ground Station Oberpfaffenhofen (OGSOP). The QUBE mission foresees that the Ludwig-Maximilian University of Munich and the Max Planck Institute for the Science of Light (MPL) provide experimental QKD signals from their in house developed payloads which are coupled into OSIRIS4QUBE using a fiber network [5].

The OGSOP is foreseen as receiving ground station for signals sent by the satellite. Updates towards the quantum key exchange were necessary to reach the project goals.

The following list is an excerpt from the work packages, done by the ground station team to enhance the quality of the OGS as a QKD-Ground station:

- Redefining Coudé path and relay lens system Rx
- Update alignment Coudé path
- Update alignment uplink beacon system
- Software update EDFA-beacon system
- Rebuild Coudé table receiving setup
- Build up preliminary QKD signal receiving setup
- Reconstruct adaptive optics (AO) path (ongoing)
    - Upgrade and resize AO relay system
    - Upgrade deformable mirror
    - Improvement of fiber coupling
- Pointing acquisition and tracking (PAT) on Coudé table
- Enabling Software derotation
- Integrate power measurement for incoming signal at various positions (parallel to OGS optical path and inside receiving system)

II. QUBE SATELLITE

A. *Satellite description*

QUBE (Fig. 1) is a 3U sized CubeSat (30cm X 10cm X 10cm), built by the Center for Telematics (ZfT) in Würzburg, with contributions from DLR, LMU, MPL/FAU and OHB as an industrial partner [14]. It is designed and developed to demonstrate technologies in preparation for QKD from CubeSats. It was launched on Transporter Mission 11 on 16th of August 2024.

TABLE I. MAIN SPECIFICATIONS QUBE

Item	*Value*	*Unit*
Satellite type	CubeSat	3U
NORAD ID	60476	--
Sun Synchronous Orbit	460 x 463	km
Inclination	97,4°	deg
Wavelength terminal	850, 1550, 1571	nm
Output Power (1550nm)	100	mW

On board it carries the following experimental payloads from the participating research facilities[14]:

MPL/FAU:

- QRNG – Quantum random number generator
- QKD signal transmitter 1571nm
- PCON, payload controller

LMU:

- 850nm QKD signal transmitter

DLR:

- Triplexer
- OSIRIS4QUBE, 1550nm

Fig. 1. QUBE Satellite

The core of the transmitting system is DLR’s laser communication terminal OSIRIS4QUBE (Fig. 2), an evolution of OSIRIS4CubeSat[14]. All transmitted signals are coupled together (triplexer) in the terminal and then sent through free space down to earth.

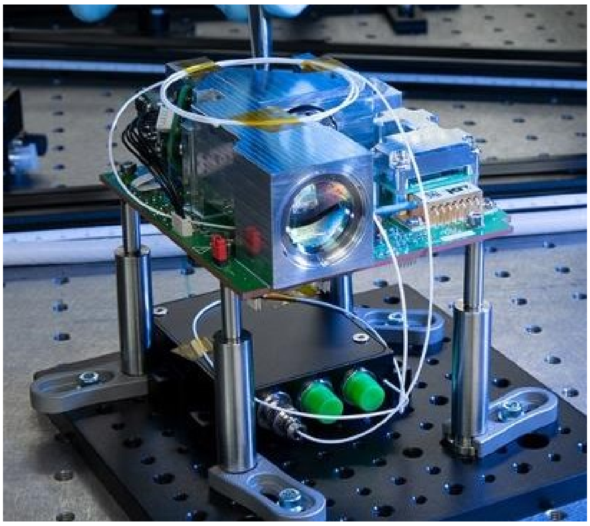

Fig. 2. OSIRIS4QUBE EQM

B. *Commissioning QUBE*

Following the successful launch of the QUBE satellite, the Launch and Early Orbit Phase (LEOP) has reached its key milestones [2][14]. This phase included the activation of the Attitude Determination and Control System (ADCS), the calibration of the sensors, the commissioning of the optical terminal and the Quantum payloads as well as the resolution of communication and software issues [2] [15]. Some Key Milestones were:

- Successful detumbling for spin rates from 2,5°/s to 4°/s [15][14]
- Magnetometer successfully calibrated and in service[14]
- ADCS in service, fine pointing <0,5°[15]

The satellite, equipped with advanced sensors and actuators, demonstrated critical attitude determination and control capabilities. Early operational tests included de-orbit, safe spin rate adjustment, fine pointing mode and verification of the optical terminal and quantum payloads [15].

The commissioning and checkout of the OSIRIS4QUBE optical laser communication terminal is described in section V.A Downlink and PAT – Experiments (DLR – ZfT).

III. Optical Ground Station Oberpfaffenhofen

The Optical Ground Station Oberpfaffenhofen (Fig. 3) was put into service 2022 as next generation station.[4]. It supported several satellite missions, particularly worth mentioning the data reception from CubeL in the PIXL-1 mission: A picture from the Munich Area, which was taken by the satellite itself was transmitted to Earth via the CubeLCT, the world's smallest laser communication terminal. In this major achievement (the demonstration of an operational end-to-end chain, including data generation, encoding and decoding), the OGSOP performed as reception unit. The used configuration was OGSOP Nasmyth-Port 2 (TABLE III.), supported by Side-Port 1 and Uplink-Beacon-System (UBS) (TABLE IV.

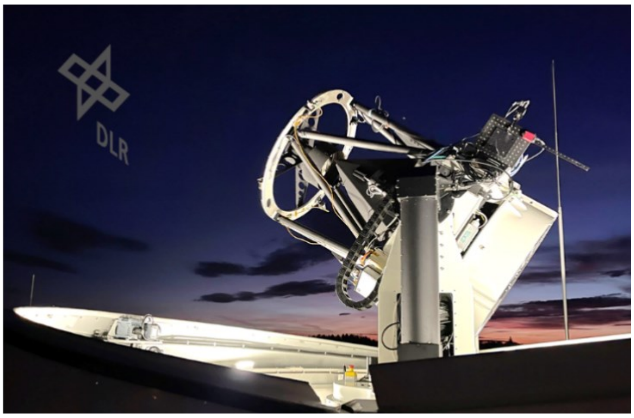

Fig. 3. Optical Ground Station Oberpfaffenhofen (OGSOP)

TABLE II. Main Specifications OGSOP

Item	*Value*	*Unit*
Geographical latitude	48,0848° N	deg
Geographical longitude	11,2780° E	Deg
Altitude above sea level (nm)	650 (+/- 1,5)	m
Telescope aperture	800	mm
Focal length	5,59	m
Back-focal length	918,355	mm
Nasmyth Ports	4	--
Coudé path	1	--

The Optical Ground Station is hosted by the Institute of Communication and Navigation in Oberpfaffenhofen, a suburban area close to Munich.

A. Telescope and Coudé path

The core of the Optical Ground Station in Oberpfaffenhofen is the receiving telescope. It is a Ritchey-Chrétien with a third flat mirror to work in Nasmyth-configuration.[4] The telescope acts as the main receiver and transmitter. It is installed on an altitude-azimuth mount.[4] The technical control is built up with three interfaces: telescope control for the mount and moving; Pointing Acquisition; Tracking (PAT) and Visual Tracker (VT) [4]. Main updates on the telescope side were changes in the Nasmyth port system with partly new equipped platforms, mostly to handle classical laser communication more efficient and freeing some space for QKD and channel characterization measurement devices.

TABLE III. Nasmyth-Ports OGSOP

Nasmyth-Port	*Equipment*	*Wavelength (nm)*
Nasmyth-Port 1 (Coudé path)	Optical table (M-RS2000) 1200x2400mm	589, 850, 950, 1064, 1550
Nasmyth-Port 2 (Sharkfin)	Optical bench 300x300mm	>950, 1550
Nasmyth-Port 3 (Swing)	Optical bench 500x500mm	free
Nasmyth-Port 4 (Vogelhaus)	Thorlabs Cage and Constructions Rails	>950, 1550

According to the port changes the side installation scheme also changed and new devices were mounted:

TABLE IV. Side - Installations OGSOP

Location	*Equipment*	*Aperture (mm)*	*Wavelength (nm)*
Side-Port 1 Primary Mirror	External infrared Acquisition camera	75	1550
Side-Port 2 Primary Mirror	Celestron C5 Visible Tracking Camera (Allied vision G-031)	127	visible
Side-Port 3 Primary Mirror	Femto-Powermeter (OE-200-IN Custom)	50	1550
Outer Spider Ring	Two Beacon launch Collimators for LEO Satellites (UBS)	5	1590 (4W output power each)
Outer Spider Ring	Imaging Source Aircraft detection Camera	20	visible

For ground-to-ground tests with the QKD signal receivers the facility at the Test-Source-Tower (TST) (Fig. 4) was also improved. An 850nm test source was installed, additional

QKD signal transmitters are currently under development. The TST is a telecommunication tower near Oberpfaffenhofen, at a distance of about 6,6km (Fig. 4). It contains a test link source out of seed laser, EDFA (Erbium Doped Fiber Amplifier), motion control, control computer and transmitting optics. The system can be controlled remotely by the telescope operator[4]. Further upgrades will lead to a full free space terrestrial QKD Link testbed in 2026/2027.

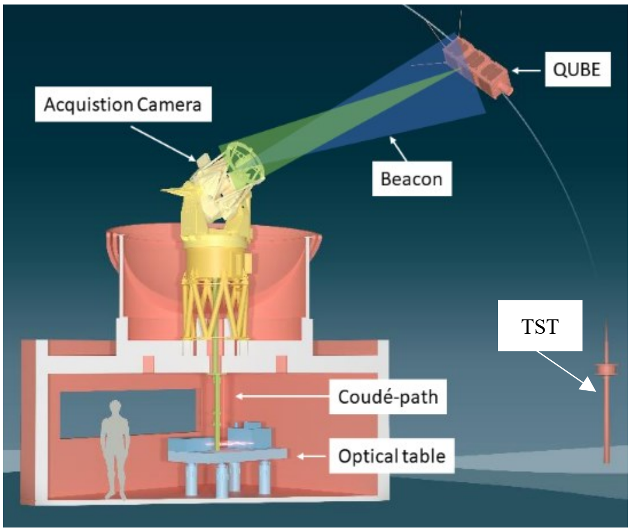

Fig. 4. OGS Overview with QUBE and Test-Source-Tower[2][4]

The Coudé path of the telescope was completely realigned with a new DLR developed process. The intension behind this was, to improve the optical quality of incoming light down at the Coudé table. Due to the upgrade of the adaptive optics system, several issues lead to this necessity. Field and image rotations were corrected, as well as wobbles and wrong angles of the incoming beams. The maintenance of the alignment is now easier and the pointing accuracy is more independent from the classical astronomical pointing model.

B. Coudé table

For receiving and processing the light on the optical bench in the laboratory, several setups are established. Incoming light is distributed to dedicated measurement devices and experimental equipment see Fig. 6.

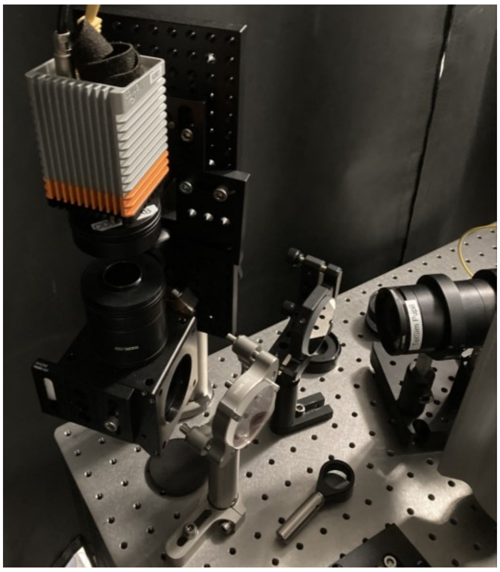

Fig. 5. PAT-Camera setup on Coudé table

To enable PAT controlled and measured from the Coudé table a dedicated setup was installed. It contains a 98:2 Beamsplitter for guiding as much light as possible to the measurement devices and use only 2% of it for PAT. Currently a Xenics Bobcat 320 is used but will be upgraded in Q1 2026 to a Bobcat 640 to expand the field of view projected on the Camera (Fig. 5). A dedicated calibration method is under development, to use this camera also for scientific purposes.

The upgrade on the table also includes a new built-up telescope simulator (TSIM). This small setup is installed in parallel to the end of the Coudé path to provide alignment and calibration sources. The simulator imitates what one would see through the telescope at the end of the Coudé path when looking at a point object on the telescope's optical axis. Coupled with the Coudé table optical setup, it provides access to a pupil plane needed for adaptive optics alignment and a focal plane, needed for acquisition camera and fiber alignment.

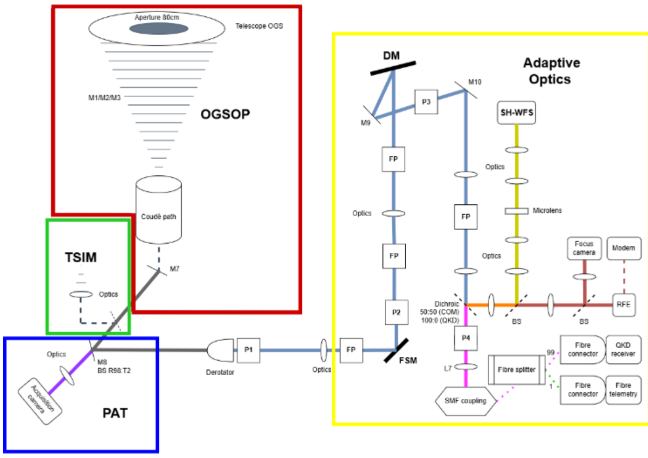

Fig. 6. Coudé table block diagram

To optimize the coupling of the received downlink signal into a single mode optical fiber, an adaptive optics (AO) system (Fig. 7) is required to correct for atmospheric turbulence which distorts the wavefronts that enter the telescope[6]. The turbulence introduced degradations of the wavefront are measured using a Shack-Hartmann wavefront sensor (SH-WFS), which drives a fast steering (tip-tilt) mirror and a high-order deformable mirror (DM) [6]. Coming from a 13 x 13 sub-aperture SH-WFS sensor the update led to 29x29 sub-apertures and a 5kHz target frame rate. The deformable mirror is upgraded from a ALPAO DM192 to a ALPAO DM820 with 32x32 actuators. The relay lens design was improved from 2” diameter COTS parts to 3” diameter customized optics for better image quality and throughput optimization. End-to-end simulations have been performed to evaluate the SMF coupling loss of the new AO system[16]. The strongest and weakest turbulence conditions are expected to correspond to r_0 values of 4.7 and 19.4cm (defined at zenith and 1550nm). The baseline scenario is r_0= 19.4cm (at zenith) at 20 degrees elevation, which indicates a median SMF coupling loss of -3.0dB [16]. The AO system is controlled by an in-house developed low-latency real-time control software running on a high- performance server computer. A free space photo-diode is used to measure the total light received by the OGS and a focus camera measures the quality of the corrected focus spot [4][10].

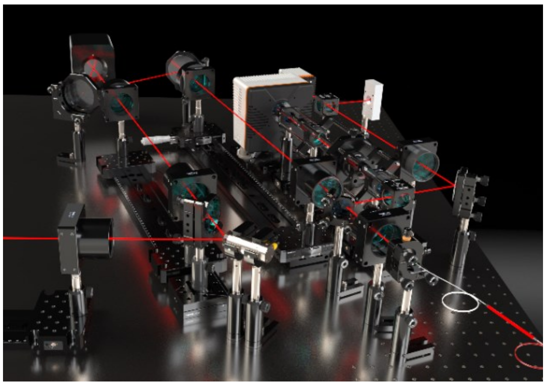

Fig. 7. Visualization of AO Upgrade on Coudé table

Due to customized dichroic filtering in the AO-loop it is possible to do free space splitting of classical communication and QKD signals. Within the QUBE downlink signal the classical communication path at 1550nm is used to transfer the reference clock signal for the 1571nm QKD signal for MPL and for the 850nm signal for LMU.

The AO system is developed and supported by the "Mitigation of Atmospheric Impairments" (MAI) group in the institute for communications and navigation, DLR.

C. QKD Receiving Upgrades

The installation of the adaptive optics system increases the fiber coupling efficiency. The light coupled in is transmitted via dark single mode fiber into a SNSPD (Superconducting Nanowire Single-Photon Detector) from ID Quantique (ID281). The coupling to other fiber-based photon detectors or similar equipment is now easily possible, due to updates in the optomechanical interface. First experiments with our SNSPD were already carried out within QuNET (AO-System 2023-2025) and preliminary measurements for Eagle-1 (static mirror system, no closed AO loop).

IV. First Light QUBE

During the satellite commissioning phase lead by the ZfT, on May 2nd 2025 the OGS Oberpfaffenhofen was able to catch the transmitted signal from satellite QUBE and received the first light (Fig. 10). QUBE also acquired the beacon signal sent from the OGSOP [2]. The predicted flight pass on sky can be seen in Fig. 8[9], an overlay with the allsky camera picture during the pass is shown in Fig. 9.

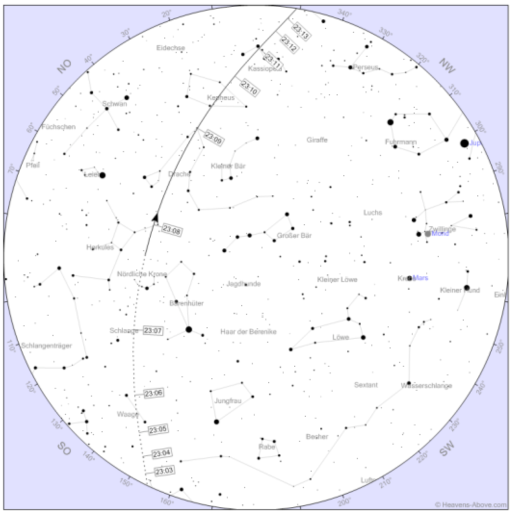

Fig. 8. Flight pass QUBE over OGSOP, 2nd of May 2025 [9]

TABLE V. Flight pass description QUBE [9]

Event	*Time (UTC)*	*Altitude*	*Azimuth*	*Distance (km)*
Rise	21:02:14	0°	153°(SSE)	2616
Reaches altitude 10°	21:04:19	10°	148°(SSE)	1748
Maximum altitude	21:07:59	52°	72°(ENE)	667
Drops below altitude 10°	21:11:46	10°	356°(N)	1802
Sets	21:13:57	0	352°(N)	2707

The signal was first seen at 10° elevation, even through thin cloud coverage (see Fig. 9). The time of the first optical contact was 21:04:19 UTC. On the satellite side the optical output power of the laser communication terminal was limited to 30mW (instead of max. 100mW).

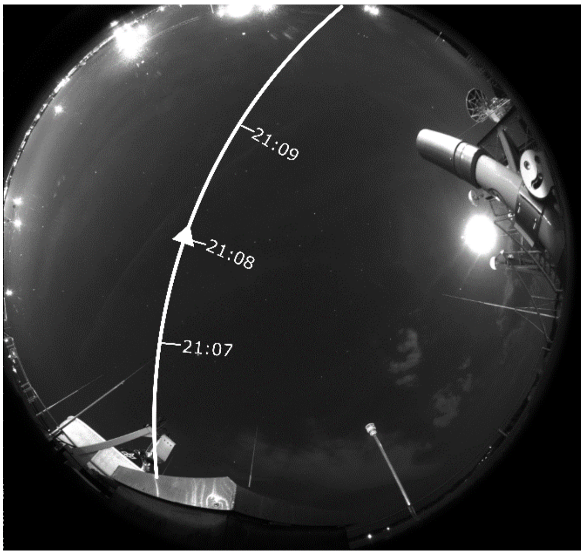

Fig. 9. Allsky camera view, 2nd of May 2025, 21:05UTC

First tracking was achieved by the external infrared Acquisition Camera (Side-Port 1 Primary Mirror) (TABLE IV. . The signal was guided through the Coudé path and handed over to the PAT-Camera setup on the Coudé table (Fig. 5).

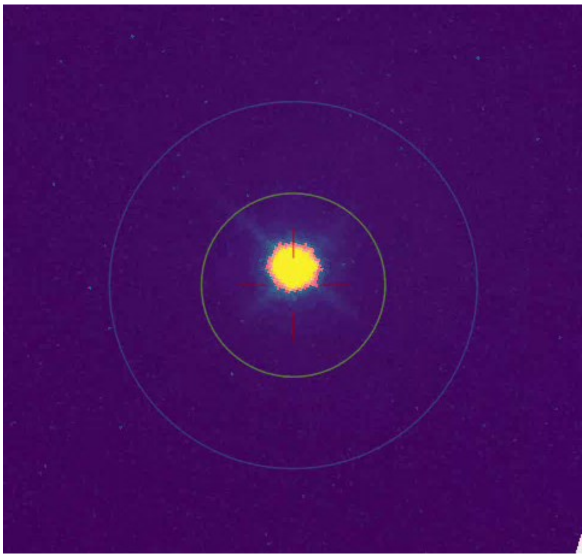

Fig. 10. QUBE First light on Coudé table at OGSOP

During around 75% of the pass the OGSOP was detecting the satellite laser signal. The remaining 25% without light from the satellite were probably due to the light cloud cover we had that night (Fig. 9).

V. Experiments and Campaigns

After first light was detected and verified, the research work on optimizing the link between satellite and ground station started. Besides dedicated campaigns, work was parallelized to enhance the scientific output and to gain knowledge for upcoming missions.

TABLE VI. Optical Link Overview QUBE

Item	*Attempts*	*Successful*	*Bad weather*	*Technical issues*
Total	24	---	---	---
DLR	24	9	11	4
LMU	5	0	4	1
MPL/FAU	Pending	Pending	---	---

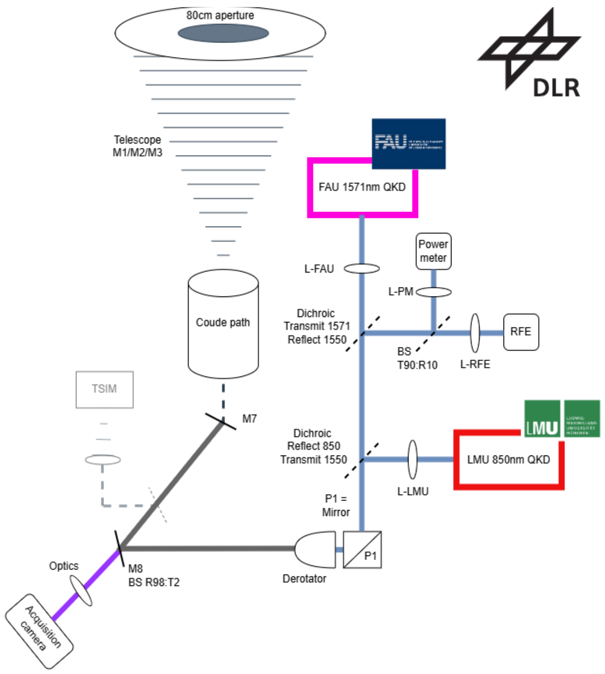

Fig. 11. Schematic overview QUBE Setup at OGSOP, October 2025

Due to the ongoing process of upgrading DLR's AO setup, a temporary solution was built to conduct first experiments with the QKD signals from LMU and FAU. This setup works without wavefront correction, but only makes use of the lower-order tip-tilt correction of the closed-loop PAT.

A. Downlink and PAT – Experiments (DLR – ZfT)

The first experiments were done to commission the optical signal from the OSIRIS4QUBE terminal. The signal could be received repeatedly and predictable. Several links were performed to optimize the quality of the incoming classical signal at 1550nm. Low-frequency fluctuations in intensity were detected with the OGS. To exclude a potential misalignment between the transmit and receive path in OSIRIS4QUBE, intensity peaks were compared with the satellite attitude and pointing direction, revealing no correlation [2].

Including October 2025 in total nine successful links with acquired optical signal could be performed. The optical connection between QUBE and OGSOP lasted over 45min in total. Ten links in total were performed so far, 11 planned links where canceled due to bad weather at the ground station side.

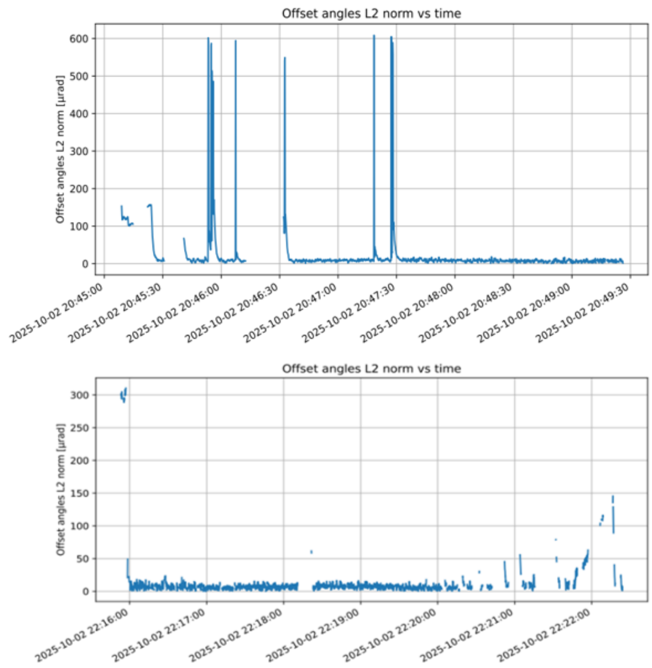

Fig. 12. Offset angles for tracking accuracy at OGSOP, during two links on the 2nd of October 2025

The aimed tracking accuracy at OGSOP is being better than 50 µrad. As exemplary shown in Fig. 12 this could be achieved during several different links. The gaps and high spikes are correlating to: no spot seen, clouds/fog, signal fading and wrong spot detections.

Due to a miscalculation (corrupted GPS data), tracking on a cpf file from QUBE was not possible during the analyzed link shown in in Fig. 12, Fig. 13 and Fig. 15. The tracking performance of the OGSOP was done with a several hours old TLE file from the publicly available website heavens-above.com.

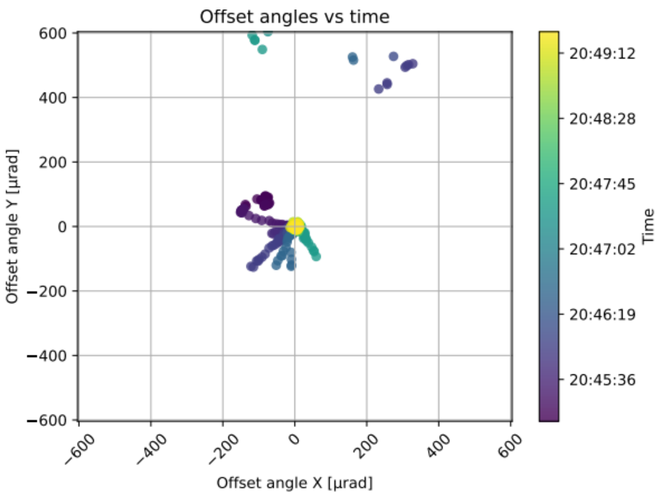

Fig. 13. Offset angles spot plot at OGSOP, 2nd of October 2025

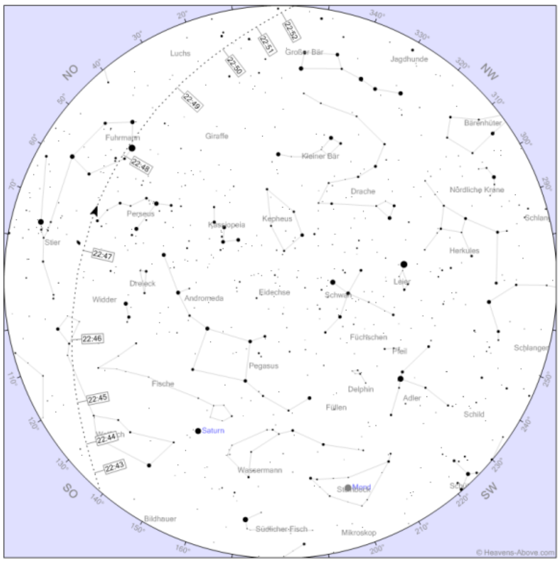

Fig. 14. QUBE pass, 2nd of October 2025[18]

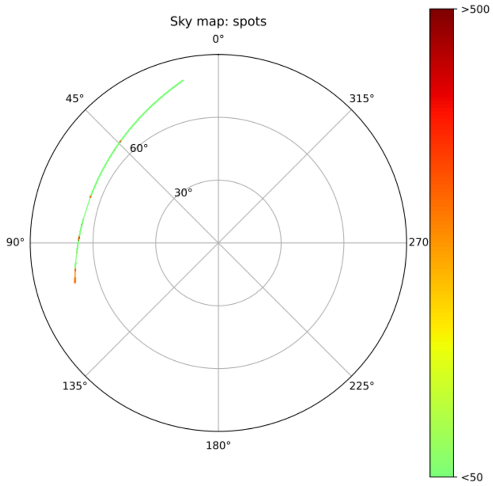

Fig. 15. Sky plot, spot detected and offset angle value, 2nd of October 2025

The comparison of Fig. 14 and Fig. 15 shows the parts of the overflight where a signal spot was detected and at which positions on sky the tracking of the OGSOP was in the green area. The link could not be performed over the hole pass, at the beginning cloud coverage made it impossible to establish a connection earlier. At the end of the pass another tracking experiment on satellite side was tested and led to no signal on ground.

Fig. 16. Clock signal from QUBE at OGSOP, 2nd of October 2025

The 1550nm signal from OSIRIS4QUBE is guided in the OGS to a Receiver Front End (RFE) (Fig. 11). The clock signal for the QKD experiments is received there. The green part in Fig. 15 also correlates to the clock signal during this particular link. The longest uninterrupted period of receiving a stable clock was over 90 seconds (Fig. 16).

B. Campaign 850nm Transmission (LMU – DLR – ZfT)

The goal is to verify the functionality of the photon source from LMU installed into the satellite. The technology behind this QKD source is based on the polarization encoding method [2]. First tests were run beginning of October 2025. In Fig. 11 the placement of the LMU receiving setup is shown. An EXCELITAS photon counter Module (Type SPCM-850-14) is installed after the dichroic mirror that splits the 850nm wavelength to the LMU setup. The functionality on OGSOP side was tested with the TST facility (Fig. 4, III. A). First tries to receive signal from QUBE hasn't been successful so far, in both attempts beginning of October 2025 no 850nm QKD signal could be detected. Investigations were done and new attempts planned, sources of errors excluded. Unfortunately, due to bad weather at OGSOP side, no further experiments took place until end of October 2025. As soon as the next clear sky period is coming the 850nm experiments are continued.

C. Campaign 1571nm (FAU/MPL – DLR – ZfT)

The FAU/MPL Team installed their receiving setup after a customized beam splitter that separates the 1571nm QKD signal from the 1550nm clock signal (see Fig. 11). This setup will attempt to inject light into a fiber without adaptive optics. The used QKD technology here is based on phase space encoding [2]. The aim of these experiments is to verify that the light source on the satellite is emitting photons that can be detected. A SNSPD provided by FAU is used as detector. The assumption to couple enough light from the 1571nm light into a 10µm fiber is based on the high tracking accuracy and the low tracking errors shown in the first links (see V. A, Fig. 12, Fig. 13, Fig. 15). This setup was built up in calendar week 42/43 2025), first experiments are planned as soon as possible, depending mainly on the weather forecast.

D. Future Multimission - Campaign (FAU/MPL - LMU - DLR - ZfT)

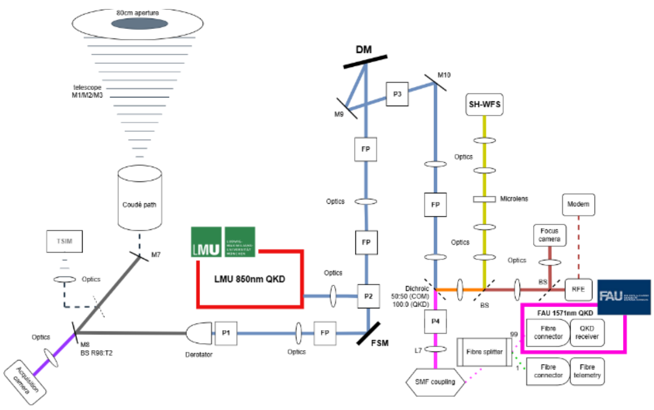

Fig. 17. Schematic overview of final QUBE Experiment Setup at OGS OP

After the final integration and commissioning of the AO setup (planned in Q4 2025 to Q1 2026), the QKD signal receiving pick-up points will change (Fig. 17). The LMU setup will be directly placed after a fine steering mirror (FSM). This mirror is controlled by the AO loop corrections, calculated from the SH-WFS inputs of the received light. The FSM will do a tip-tilt correction. This type of setup was already proven during the end-to-end tests with OSIRIS4QUBE in Q1/Q2 2024.

The FAU setup will move to the end of the AO controlled loop and will directly make use of the fiber coupling station in the adaptive optics setup.

VI. Conclusion

After the first promising results with the QUBE Satellite the way forward is clear.

TABLE VII. Roadmap QUBE

Involved Entity	Roadmap for QUBE		
	Experiment description	***First experimental commissioning***	***Final experimental campaign***
DLR	OGS receiving light, tracking, providing light and clock signals to the partner experiments	May 2025	Q2/Q3 2026
ZFT	Satellite ready for partner experiments	until May 2025	Q4 2025
LMU	850nm QKD signal tests	planned from October 2025	Q2/Q3 2026
FAU/MPL	1571nm OKD signal tests	planned from October 2025	Q2/Q3 2026

After the commissioning of the new adaptive optics system on the Coudé Bench, the QUBE QKD-experiments will be redone. The adaptive optics should increase the performances of fiber coupling, and allow to verify that the 1571nm QKD light source not only emit photons, but also emit photons at the rate we expect it.

Further work will include channel characterization measurement in the framework of the QuNET project.

The final setup will also be used as a testbed for the Eagle-1 Mission. The lessons learned from the current campaign will benefit the operation of the OGSOP during the EAGLE1 project [6].

The successor mission for QUBE will be QUBE-II, currently being integrated. The flight models were handed over to the Satellite integrator and are currently in their final integration stage. The launch is currently planned for Q2 2026. This satellite will have the goal to demonstrate a full QKD implementation between a CubeSat and the ground station.

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